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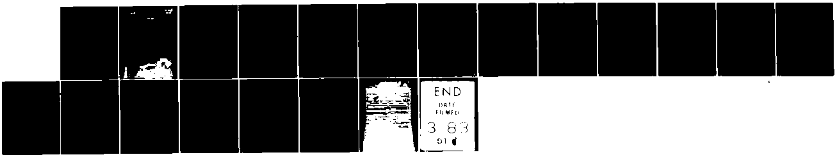

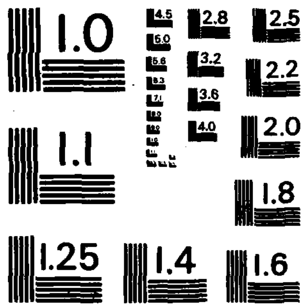

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THE DESIGN OF SHIELDED PITOT TUBES WITH SMALL SENSITIVITY TO INCIDENCE

by

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SUMMARY

The range of incidence over which a pitot-tube accurately indicates stagnation pressure in subsonic flow can be substantially increased by surrounding the pitot with a carefully designed shield. In this Memorandum the effect of some of the design variables of this shield are investigated experimentally, and a miniature probe design is described which enables an accurate indication of stagnation pressure to be obtained over an incidence range of ±57°.

degree

LIST OF CONTENTS

1 INTRODUCTION

Measurements of stagnation pressure in aerodynamic experiments are often required in circumstances where the flow direction relative to the measuring probe is not known and the incidence angle may be large. Typical examples are the measurements made during total-head surveys around wind-tunnel models at high incidence, and the pitot-probe measurements required on free-flight models during spinning investigations. Such circumstances may also occur full-scale since recent advances in combat aircraft design have enabled controlled flight to be achieved up to extreme angles of attack; under such conditions a conventional pitot tube will not measure the true stagnation pressure and the gross corrections needed are difficult to determine and apply.

In some cases five-hole probes can be used to deduce the stagnation pressure and also to provide information on the local flow direction. However, such probes require the use of an extensive set of calibration data, or the mechanical complexity of a self-aligning mechanism to null pressure differences in diametrically opposed holes. An alternative is to modify the shape of the pitot tube itself so as to increase the incidence range over which the error can be considered negligible. Gracey[1] *et al* have compared a wide range of pitot designs for this purpose and have concluded that probes with a vented shield perhaps have the least sensitivity to large flow incidence. This type of probe was first suggested by Kiel[2], although his original probe differs from those considered by Gracey in that it was mounted on a support perpendicular to the airstream rather than mounted axially.

Fig 1 illustrates the arrangement of such a shielded pitot. The function of the concentric shield is to capture a stream filament and realign it along the axial direction of a small central pitot tube. Air flow is maintained past the pitot tube by vents in the shield downstream of the measuring point. The internal contraction of the shield before this point is important since it determines the incidence range over which the internal flow remains attached, giving nearly axial flow over the central pitot and only negligible errors in the indicated stagnation pressure.

This Memorandum gives the results of an experimental investigation comparing the performance of a number of shielded-pitot designs. This investigation was made primarily to select a small probe design suitable for making some detailed flow surveys behind a wind-tunnel model where the local flow direction was expected to vary over a wide range of angle-of-attack.

2 DETAILS OF PROBES TESTED AND TEST PROCEDURE

The probe designs tested are shown in Fig 1. One aim of this investigation was to develop probes small enough to be suitable for flow survey work in restricted spaces, and a central pitot tube of 1 mm outside and 0.6 mm inside diameter was selected as the smallest size giving reasonably rapid response times. This sensing tube was chamfered to a sharp tip to decrease its incidence sensitivity[1], and progressively telescoped with short lengths of 1½mm, 2mm and finally 3mm (outside diameter) hypodermic tubing to give a reasonable degree of stiffness. This unit of telescoped tubes was tested with three different shields pushed over it, each sealed at various fore and aft locations.

The outside diameter of all three shields was 4 mm, and each had a contraction angle at the inlet lip of 45°. This lip was kept sharp for most tests but the effect of rounding was also briefly investigated. The internal nozzle profiles of the shields were manufactured without any difficulty using a tool turned to the required shape and machined to give a 'D' cross section with a cutting edge.

The probes were tested in a small 0.3m × 0.3m low speed wind tunnel at Southampton University, which has a convenient mounting enabling the incidence to be varied in the range $\pm 64^{\circ}$ whilst maintaining the tip of the probe at the same location on the tunnel centreline. Tunnel speed and the indicated probe pressure were measured on a variable-slope alcohol manometer. Most tests were made near the maximum tunnel speed of 24 m/s with some tests at lower speeds to determine whether the probe's useful incidence range was sensitive to Reynolds number. A few tests were also made with the shield vent holes at different roll orientations to the incidence plane. In all cases both positive and negative incidences were tested but only mean values are presented here for simplicity.

3 DISCUSSION OF RESULTS

Figs 2 to 4 show the effect of varying the shield longitudinal position relative to the central sensing tube, ℓ/D , for three different amounts of internal contraction of the shield inlet, d/D . These results show the difference between the measured pitot pressure, P_{tm} , and the true value, P_t , non-dimensionalised with dynamic pressure, q . In each case there is an optimum location, with the shield rapidly losing its effectiveness for small values of ℓ .

The range of incidence over which the error in stagnation pressure is within 1% of q has been used as a convenient measure of the probe's useful incidence range. The results based on this criteria are summarised in Fig 5, and clearly show the optimum value of ℓ/D for the three values of d/D . This figure also demonstrates the substantial increase in performance of shielded designs over a conventional pitot that was included in the tests for comparison. The unshielded pitot consisted of an unchamfered 2mm hypodermic tube with an inside to outside diameter ratio of $di/do = 0.74$.

The shielded probe's performance improves with increasing internal contraction (decreasing d/D) over the range tested, but this must also reach an optimum value beyond which the constriction will impair the flow through the probe and out of the vent holes.

One intriguing feature of Figs 2 to 4 is that as incidence increases, prior to the rapid fall in indicated pitot pressure, there is a small region where the sensing tube indicates pressures above the true stagnation pressure. The tip of the probe remained in the same position in the tunnel as incidence was varied, so this feature cannot be explained in terms of possible stagnation pressure gradients across the working section. Although it is a small effect ($\leqslant 0.5\%$ of q) it was large enough to be detected consistently by the instrumentation and demonstrates that, contrary to what one might expect, it is possible for a pitot tube to indicate a pressure higher than stagnation pressure. One explanation for this is that there is in this case an extra unsteady component of pressure due to stream turbulence. Provided that the scale of turbulence is small compared with

the probe diameter, a pitot tube aligned in the flow direction of an incompressible turbulent flow[3] measures*,

$$p_\infty + \tfrac{1}{2}\rho V^2 + \overline{\tfrac{1}{2}\rho (V')^2}$$

where V is the resultant mean velocity
and V' is the resultant turbulent velocity perturbation.

In the current experiments it is plausible that turbulence is generated inside the shield mouth by the shear layer separating from the lip at high incidence. Before the incidence is high enough to cause this layer to touch the mouth of the central sensing tube and give a reduction in pressure, the propagated turbulence slightly increases the measured pressure.

In steady incompressible flow, Becker and Brown[4] have shown that the effect of incidence, θ, on a wide range of different types of pitot tube can be expressed by the empirical relation:

$$P_{tm} - p_\infty = \tfrac{1}{2}\rho V^2 (1 - k \sin^{2n}\theta)$$

where k and n are constants depending on the probe geometry, P_{tm} is the measured value of the true stagnation pressure P_t, and p_∞ is the static pressure. In incompressible flow the pitot error is therefore:

$$\frac{P_{tm} - P_t}{q} = -k \sin^{2n}\theta \quad ,$$

where q is the dynamic pressure $\tfrac{1}{2}\rho V^2$.

Fig 6 shows that the conventional unshielded pitot with $di/do = 0.74$ follows this relation well over a wide incidence range, with $k = 1.70$ and $n = 2.03$. In spite of the fundamentally different flow conditions at the mouth of the sensing tube, the response of shielded designs can also be approximated by this expression once the pitot error exceeds 0.01, although for small values of ℓ/D, the variation with incidence is split into two distinct regions having different values of k and n. The best shielded probe gives an error of well below 1% of q at $\theta = 52^\circ$, whereas the unshielded pitot that was tested would give a 65% error in the same conditions.

The area of the vent holes was not varied during these tests, but the effect was investigated by Gracey[1], who found that the total vent area should be at least as large as the inlet area. Gracey's results are shown in Fig 7, compared with a single point from these present tests, interpolated to the values of ℓ/D and d/D corresponding to Gracey's design. The mismatch is no doubt due to the large difference in the angle of the shield's inlet lips. This angle was fixed at 45° for all the probes tested here, as

* This expression only applies when the physical scale of the turbulence is small. When the scale is sufficiently large, the probe responds instantaneously as if it were in a yawed flow corresponding to the instantaneous transverse velocity components, and the mean pressure recorded is then always less than the true mean stagnation pressure.

opposed to Gracey's angle of 14^{o}, as it was reasoned that this would delay internal flow separation from the lip to higher angles.

It was expected that rounding the inlet lip would inhibit the flow from separating, thus improving the probe's useable incidence range. However, it is clear from Fig 8 that rounding made the shield less effective. Fig 8 also shows the effect of turning the shield so that the vent holes are in different positions relative to the incidence plane. It can be seen that this has very little effect.

As Reynolds number decreases, the pitot error at high incidence must eventually increase due to viscous losses inside the shield. The effect of reducing Reynolds number is shown in Fig 9. A significant loss in the useable incidence range occurs for free-stream velocities lower than about 15 m/s. This value is likely to be strongly dependent on the internal geometry of the probe and vents. The Reynolds numbers shown are based on the free-stream velocity, whereas the local internal velocities inside the shield will, of course, be very much lower, especially at high incidence.

The probes shown in Fig 1 have not been tested at compressible speeds, but Fig 10 gives results for a similar design tested in the RAE 2ft × 1½ft transonic tunnel. This particular probe was designed to measure the speed of an aircraft ejector seat after ejection. Unlike the axially supported probes shown in Fig 1, the ejector seat probe is mounted on a side-strut. Fig 10 shows that the useable incidence range is only weakly affected by Mach number over the range tested.

4 CONCLUSIONS

Placing a vented shield around a pitot tube considerably increases the incidence range over which the pitot can be used before the error becomes significant. An experimental investigation of design parameters has shown that,

(i) there is an optimum position of the shield fore and aft;

(ii) increasing the shield internal contraction improves the performance over the range tested;

(iii) the shield lip should be internally chamfered at a large angle but kept sharp.

Tests elsewhere have shown that the vent holes should have a total area at least equal to the inlet area. The best of the miniature probe designs tested had $\ell/D = 0.75$, $d/D = 0.425$, a shield lip inlet angle of 45^{o} and a vent area 1.6 times the inlet area. With this probe, of overall diameter only 4 mm, the stagnation pressure measured was accurate to 0.01q over an incidence range of $\pm 57^{o}$.

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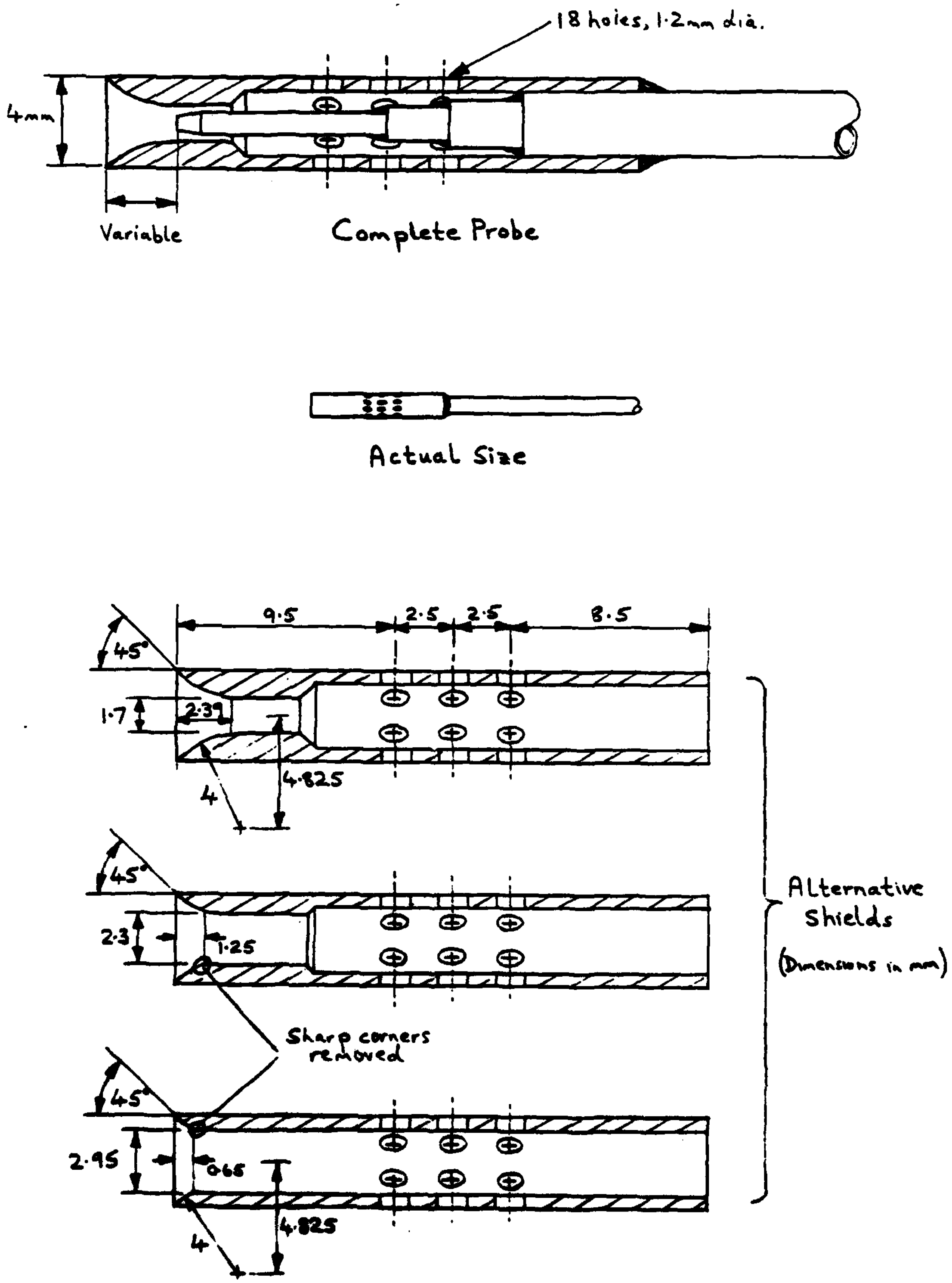

Fig 1 Details of probes

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Fig 2

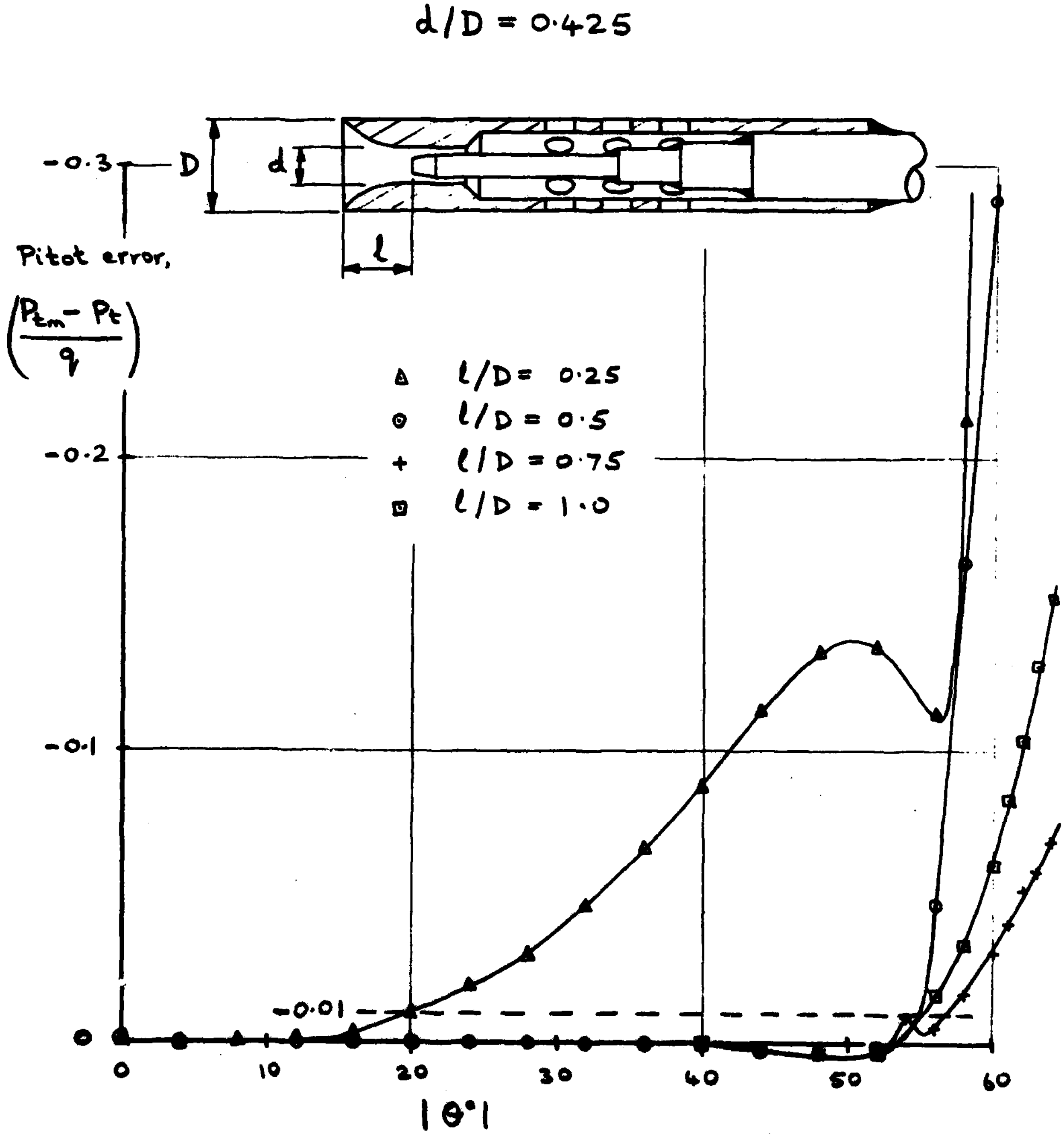

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Fig 2 Pitot error for d/D = 0.425

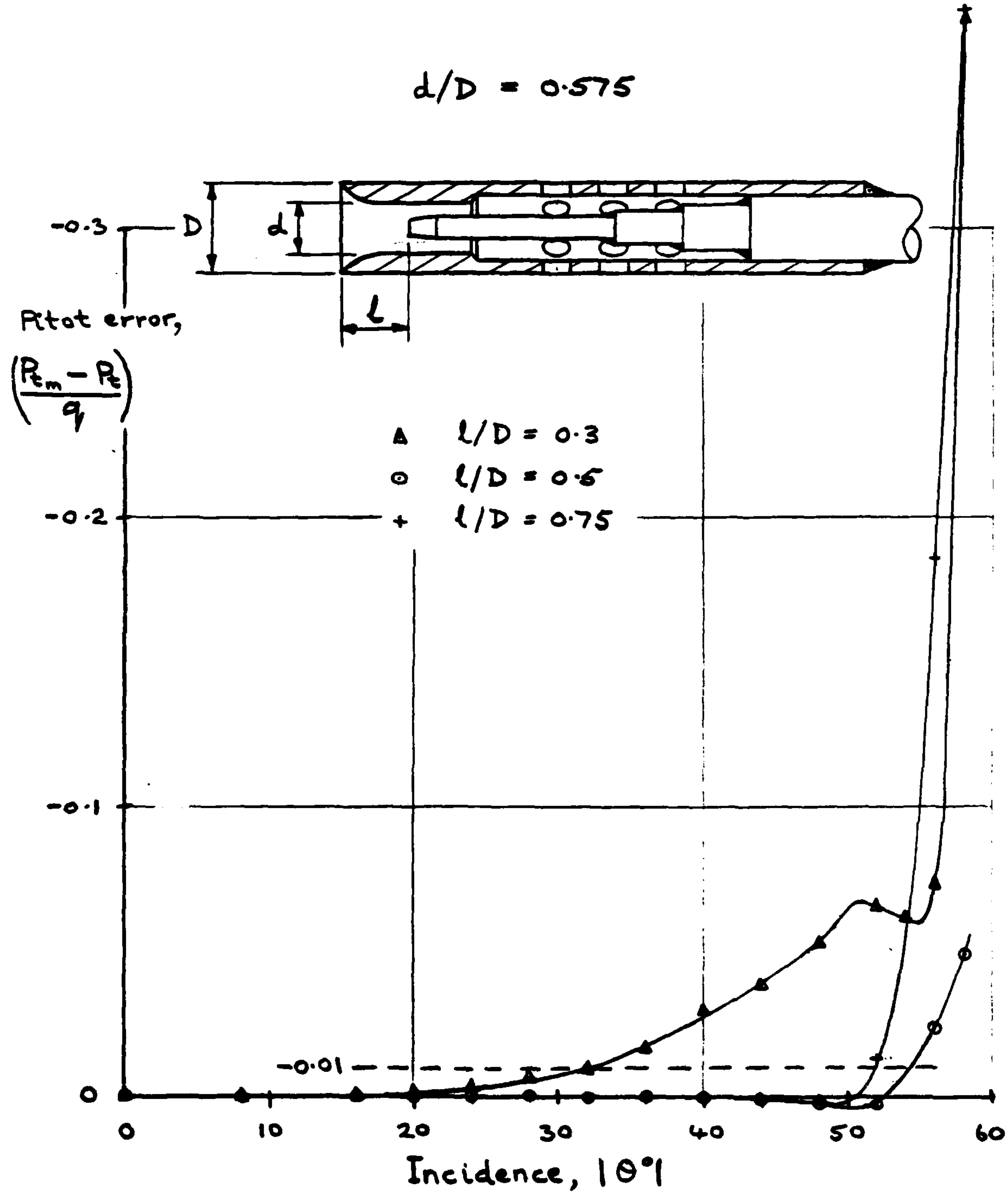


Fig 3 Pitot error for d/D = 0.575

Fig 4

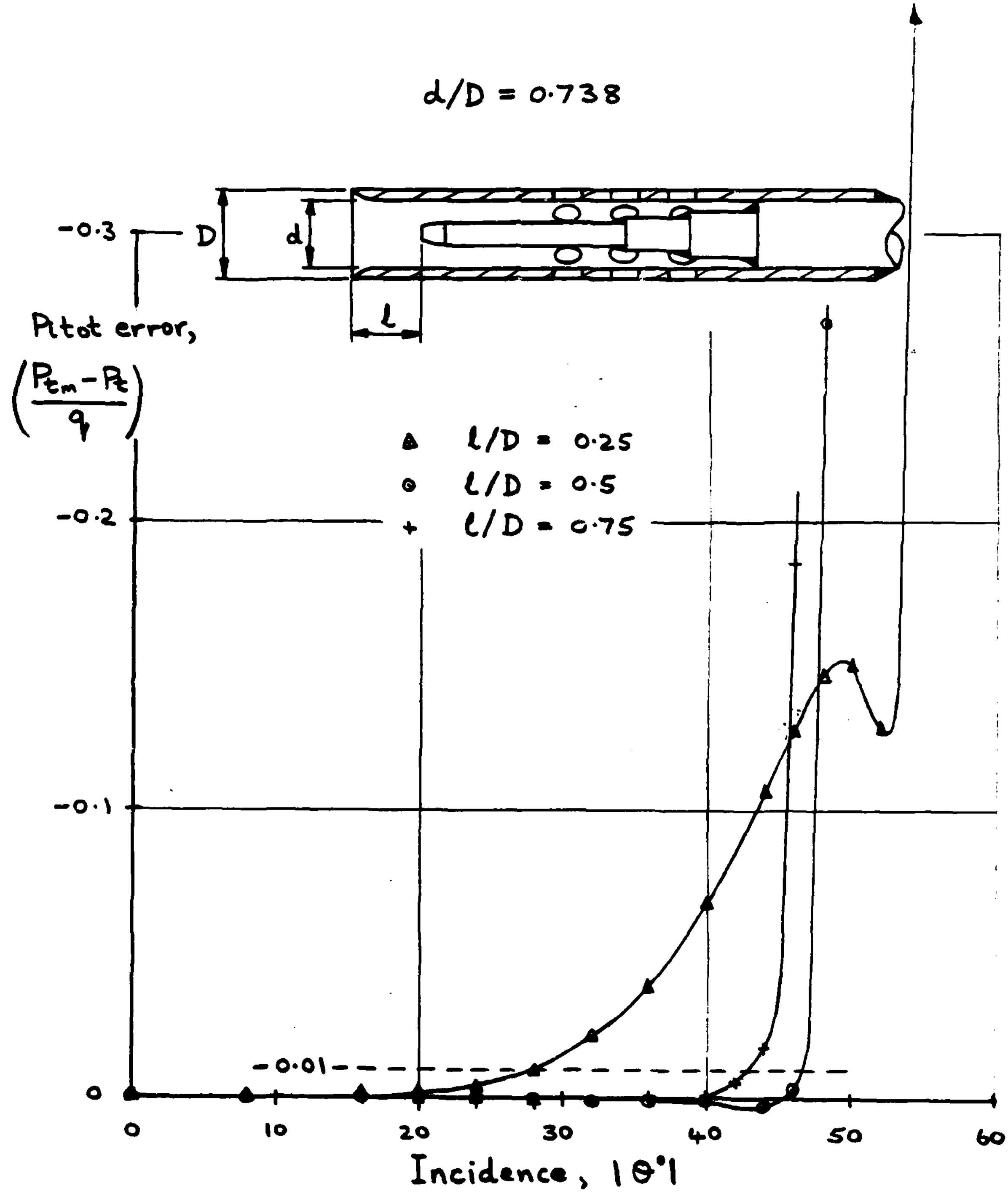


Fig 4 Pitot error for d/D = 0.738

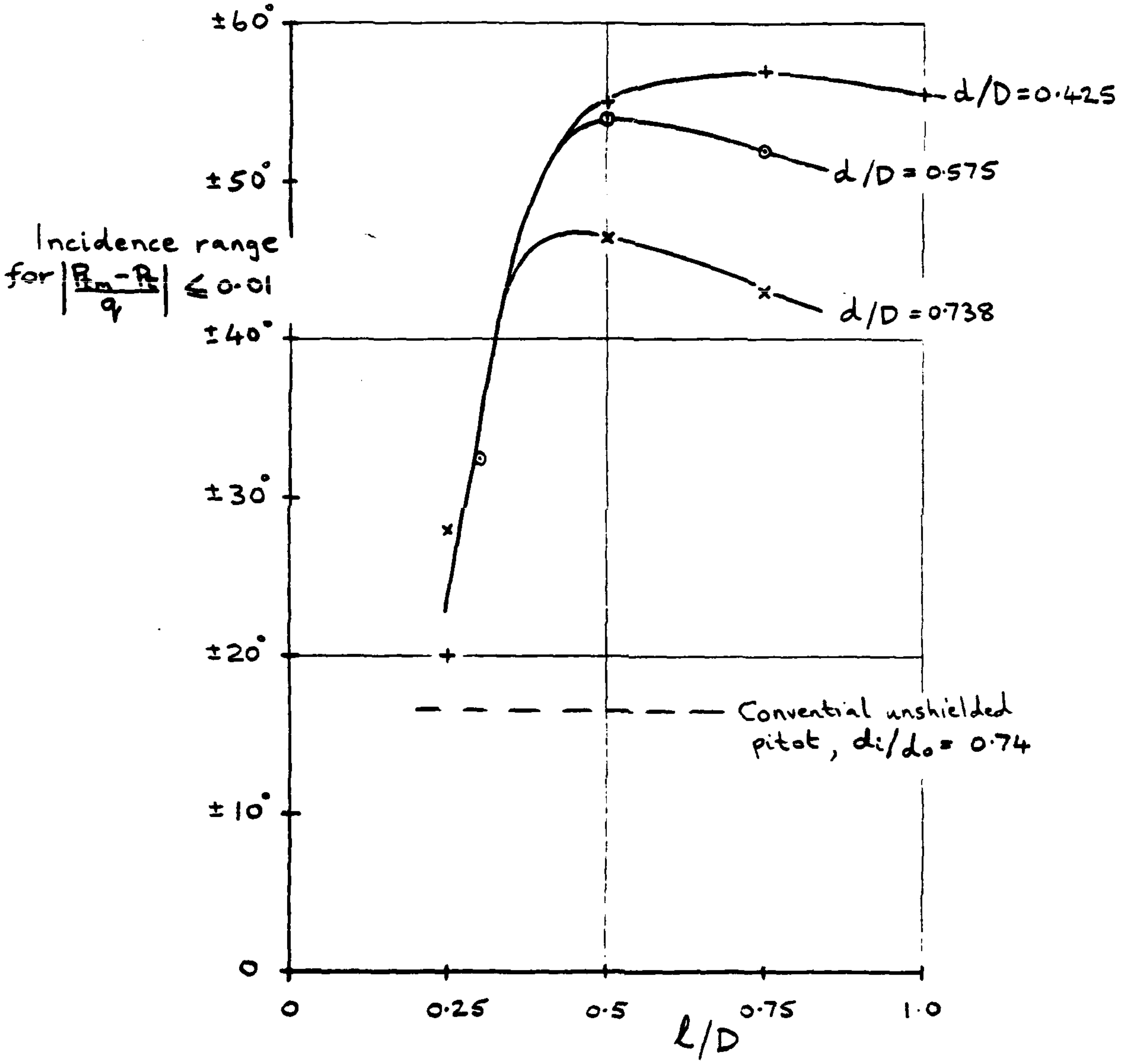


Fig 5 Useable incidence range

Fig 6

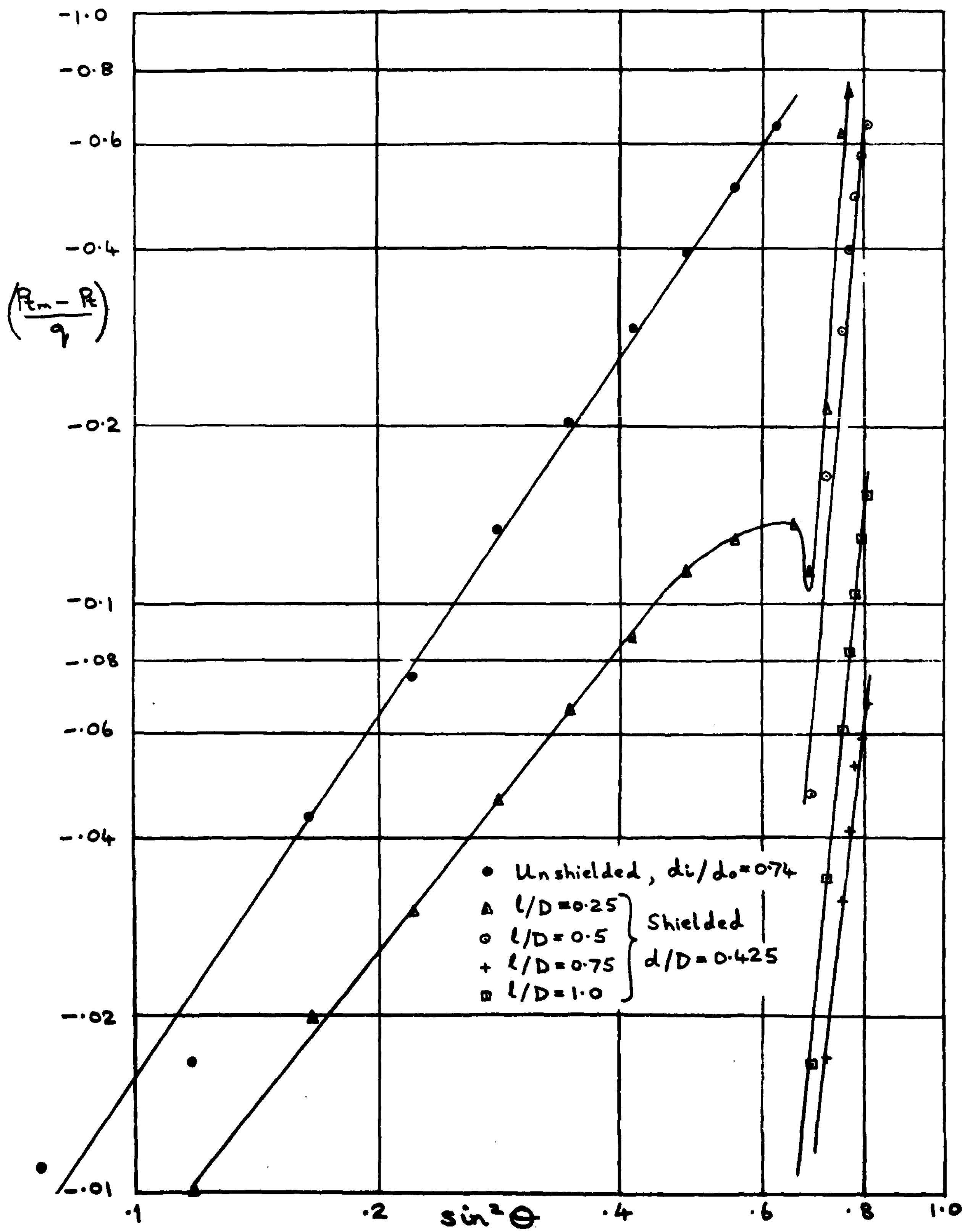
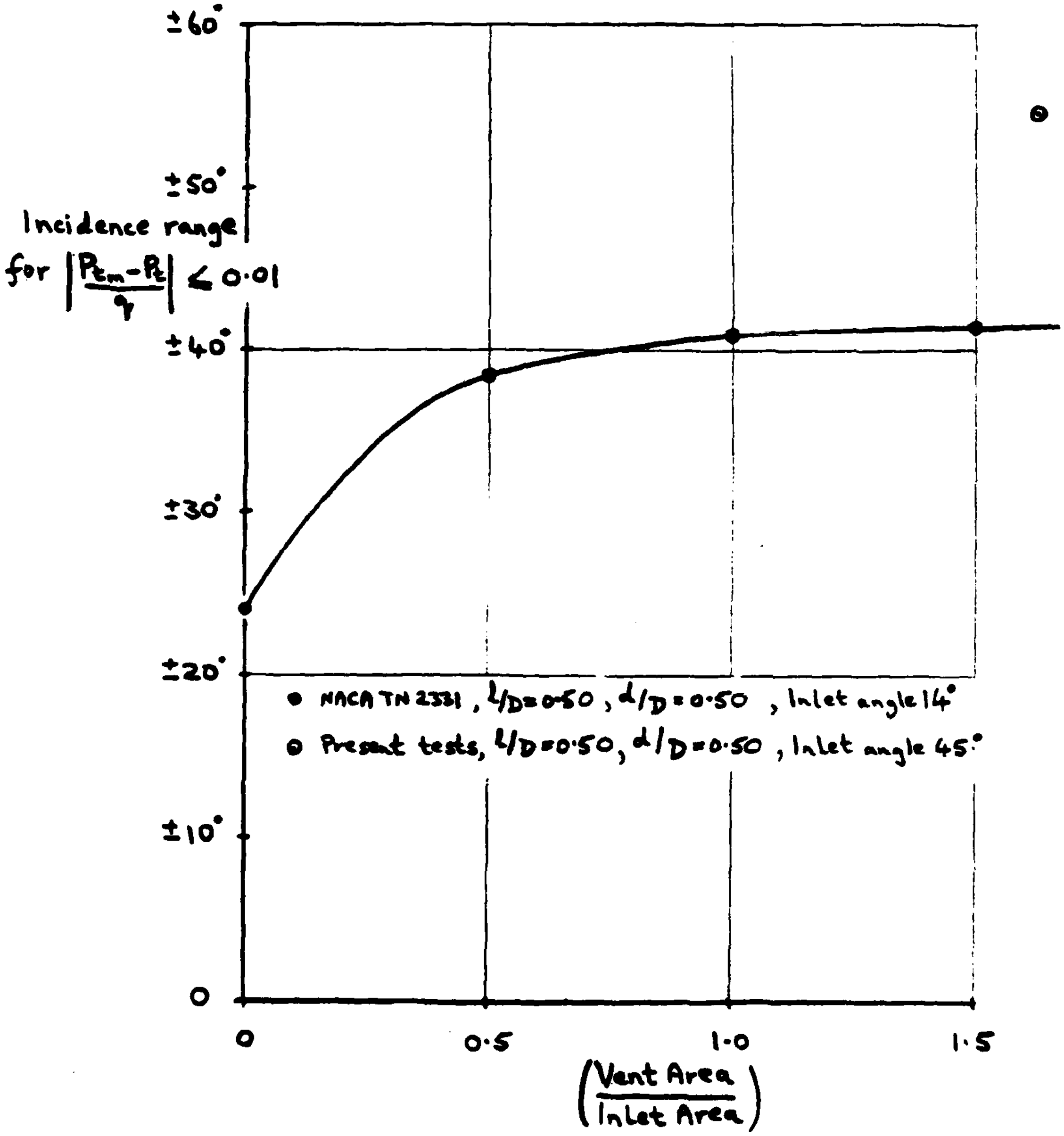


Fig 6 Logarithmic plot of pitot errors

Ae 1863



Ae 1863

Fig 7 Effect of vent area on useable incidence range

Fig 8

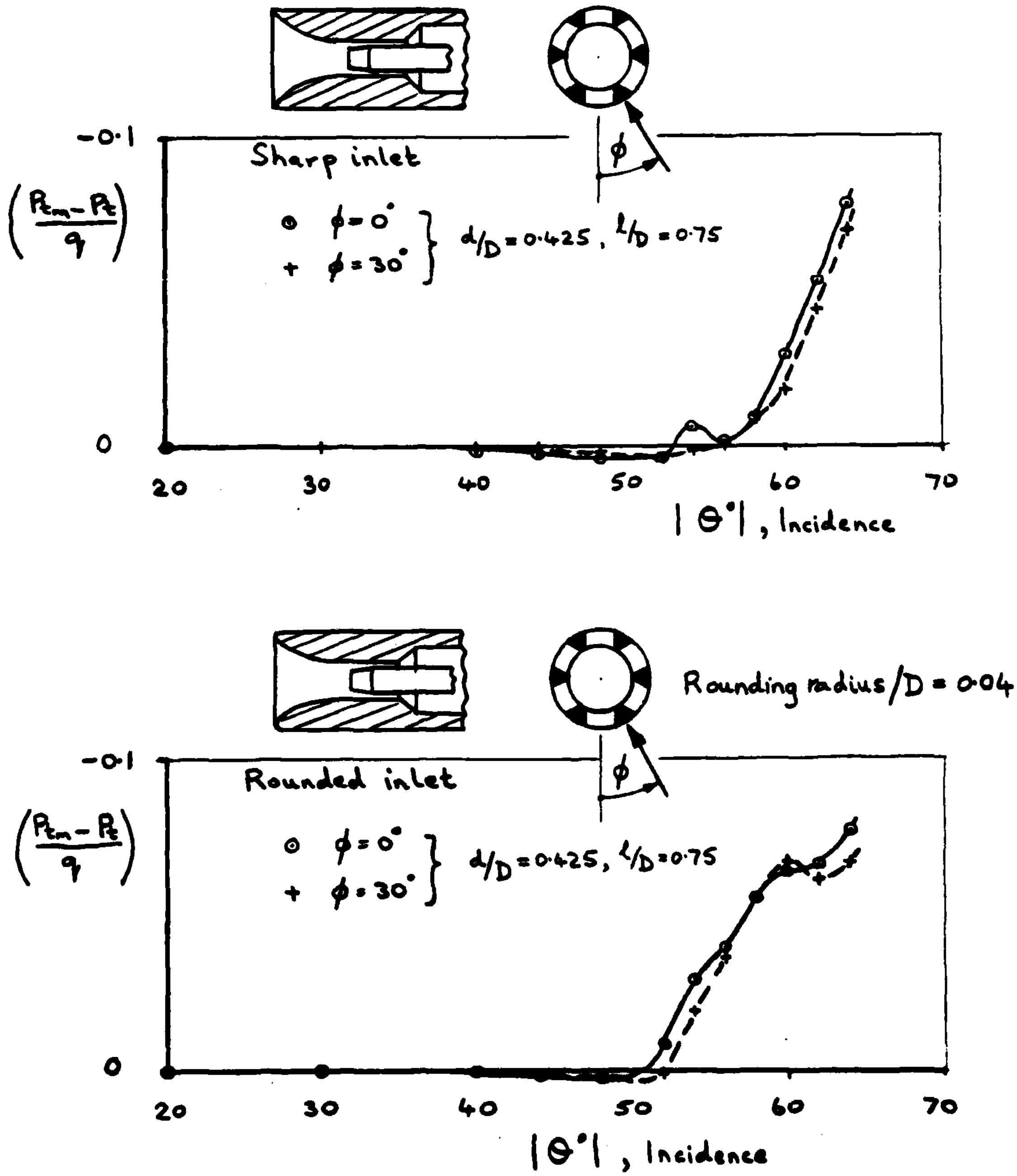


Fig 8 Effects of roll angle and rounding inlet lip

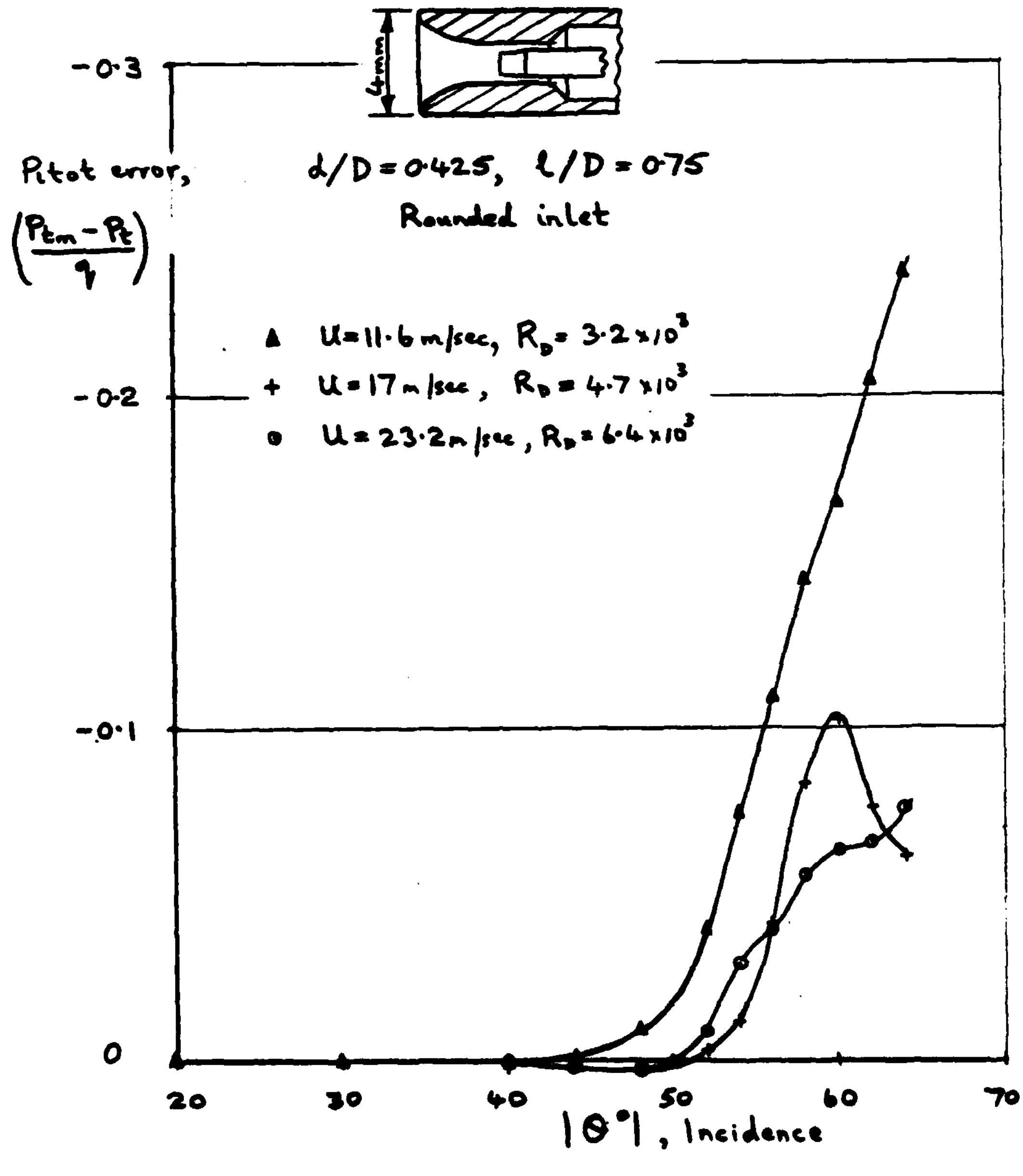


Fig 9 Effect of Reynolds number on pitot errors

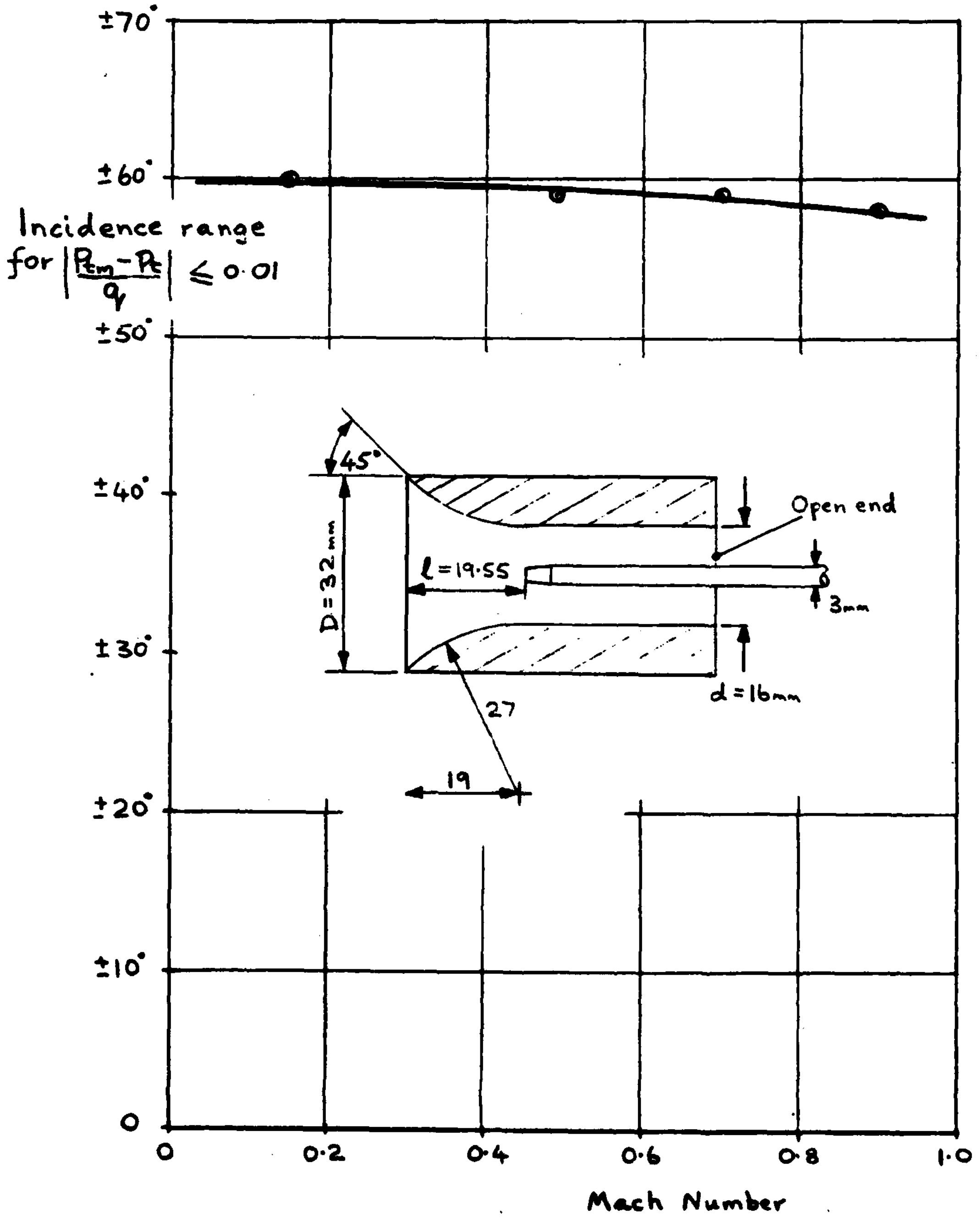


Fig 10 Effect of Mach number on pitot errors

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